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Electron-Beam-Pinch Experiment at Harry Diamond Laboratories: Providing for a High-Dose-Rate Flash X-Ray Facility for Transient Radiation Effects on Electronics (TREE) Testing of Pieceparts

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The peak photon-radiation dose rate of the Harry Diamond Laboratories (HDL) High-Intensity Flash X-Ray facility has been increased by at least a factor of five through the use of custom beam-pinching hardware. With this hardware, the facility can now routinely provide a dose rate of 2.7×10^{11} rads(Si)/s, at a distance of 1/4 in. from the drift-tube face, while providing excellent radial drop-off to minimize irradiation of items surrounding the device under test. The experimental results show the optimum operating parameters of the beam-pinching hardware to be a drift-tube length equal to 6 cm with an internal nitrogen gas pressure of 0.1 Torr.

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Contents

Figures

1. Introduction

Over the past year, data were taken at Harry Diamond Laboratories (HDL) to measure the response of radiation-hardened semiconductor devices to transient radiation.[1] These tests indicate that for input and tri-stated output photocurrents and some upset measurements, intense ($>1 \times 10^{11}$ rads(Si)/s), small-diameter photon beams are preferred over electron beams. To meet this requirement, we set about to increase the dose rate available at the HDL high-intensity flash x-ray machine (HIFX) through beam focussing; the maximum useful dose rate then available was 5×10^{10} rads(Si)/s. Our approach was to decrease the spot size of the radiation, which provides more intense irradiation of the die, with less irradiation on the associated die package, printed circuit board, and test fixture. By minimizing the radiation outside the die, signals induced by internal electromagnetic pulse (IEMP) on the circuit board would also be minimized.

The goal of these tests was to achieve a $>1 \times 10^{11}$ rads(Si)/s photon beam over about a 1-cm^2-diam area with a uniformity of better than 90 percent and a rapid falloff in the radial direction (r). Such a rapid falloff minimizes or eliminates the need for lead shielding of the circuitry near the die. The space needed for shielding forces the device under test to be farther away from the tantalum (Ta) target and consequently it receives less ionizing dose rate.

2. Approach

The approach used was to allow the electron beam to pass through the titanium (Ti) window of the HIFX tank into a drift tube with a partial pressure of nitrogen (N). At the correct gas pressure, a neutral charge region is formed within the drift tube, allowing the self-magnetic field to collapse the electron beam, which causes the beam to focus (or pinch). The pinched beam then strikes a Ta target, producing photons. The optimum gas pressure and drift-tube length were determined experimentally.

3. Theory

Calculations based on single-particle trajectories indicate that a drift-tube length of about 2.5 to 3 times the incoming electron-beam diameter will produce a pinched beam, given the energy of the HIFX

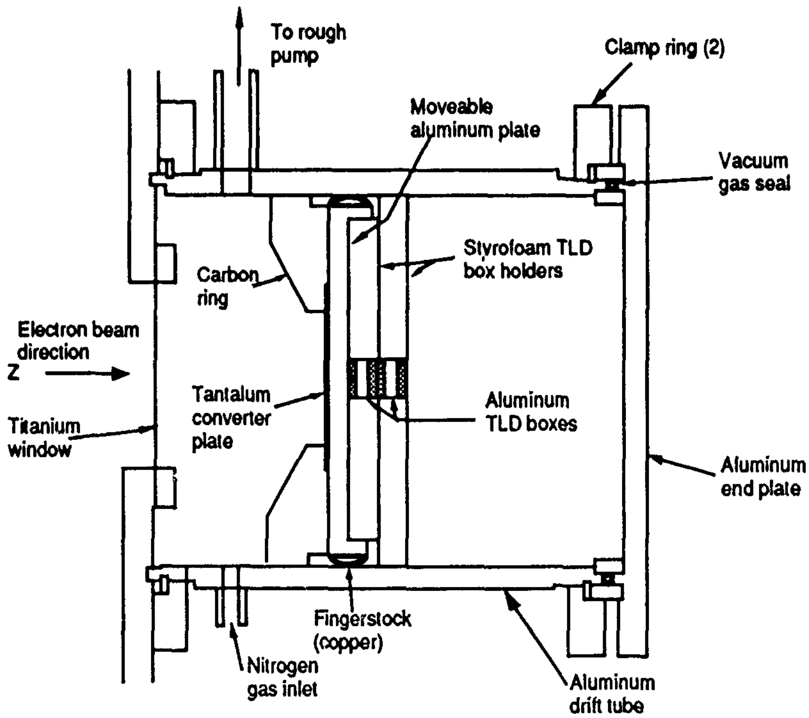
[1] *C. Self, C. Tipton, S. Murrill, H. Eisen, and G. Brucker (GE/ASD), Input and Tri-Stated Output Photocurrent in CMOS SRAMs, Harry Diamond Laboratories, HDL-TM-91-8 (June 1991).*

electrons.* These calculations assume that the drift tube is filled with a low-pressure gas which will neutralize the repulsive electric fields of electrons in the beam. With the electric forces minimized, only self-magnetic forces would act on the electrons. This analysis assumes a perfectly charge-neutralized system. The ionization fraction due to the background gas is not easily converted to an absolute pressure, so the optimum pressure must be empirically determined. Nitrogen is a convenient and readily available gas; pressures on the order of 0.1 to 1 Torr are expected to produce a charge-neutralized electron-drift region, given the total current of the HIFX electron beam.[2]

4. Experimental Design

To determine the most satisfactory pinch conditions, we constructed an apparatus (shown in fig. 1) in which drift-tube length and pressure could be varied. A 20-cm-long aluminum (Al) drift tube with an Al endplate was attached to the faceplate of the HIFX, which was operating in the electron-beam mode (Ti window in place).† A ⅜-in.-

Figure 1. Diagram of movable target drift-tube assembly.



[2]*S. E. Graybill and S. V. Nablo, Observations of Magnetically Self-Focusing Electron Streams, Appl. Phy. Lett. 8, 1 (January 1966), 18–20.*

**W. A. Seidler, Design Theory for the Pinch, private communication.*

†The electron beam exiting the Ti window is estimated to be 2 to 3 cm in diameter with the standard cone-shaped cathode (this could vary if a different cathode were used); therefore, the optimum drift-tube length is less than 10 cm.

thick movable (in the z direction—that is, normal to the Ti window) Al plate, held in place with rf fingerstock, was located within the drift tube. A 15-mil-thick by 3.0-in.-diam Ta converter plate was located in front of the movable plate. The converter was surrounded and held in place by a 1-in.-thick carbon (C) ring and shaped to roughly maintain the impedance seen by the electron beam as its diameter narrowed to the pinch. The outer perimeter of the converter was attached to the C ring with copper tape.

Thermoluminescent dosimeters (TLDs)* and a coaxial x-ray diode (CXRD) were placed in the drift tube beyond the movable plate to measure total dose and time history. The movable plate, Ta converter, TLDs, and CXRD all moved as a unit, so their relative locations remained unchanged as the drift length was varied. The drift tube was pumped down to 0.01 Torr using a roughing pump. With the pump running, N was continuously flowed through the drift tube at a rate to maintain the desired pressure level.

5. Experimental Procedure

In these experiments, the HIFX was charged to 4.1 MV, providing a photon spectral peak of 400 keV. This charging voltage is optimum for minimizing tank sparks and hence maximizing the mean time between machine failures, while providing substantial electron-beam current—about 25 kA.

For the first series of shots, the movable target was set at drift-tube lengths of 5, 6, 7, and 8 cm. For each length, shots were performed at drift-tube pressures of 0.05, 0.1, 0.25, and 0.5 Torr. Multiple shots were generally taken at each condition.

Two TLDs were used for each shot. They were held in TLD pillboxes, placed along the drift-tube central axis behind the movable aluminum plate, by mounting the pillboxes in styrofoam disks. The pillboxes are about 7⁄16 in. thick and were centered in styrofoam pillbox holders about ½ in. thick. Hence, the TLDs themselves were located about ¼ and ¾ in. from the movable plate (see fig. 1).

6. Results

Figures 2 through 5 are plots of dose rate vs drift-tube length for pressures of 0.05, 0.1, 0.25, and 0.5 Torr, respectively, for the TLD located ¼ in. from the movable plate. In the pinched-beam mode, the

**We used standard HIFX calcium fluoride (CaF_2) TLDs in Al pillboxes for electronic equilibrium.*

Figure 2. HIFX beam pinch at 0.05 Torr, ¼ in. from face.

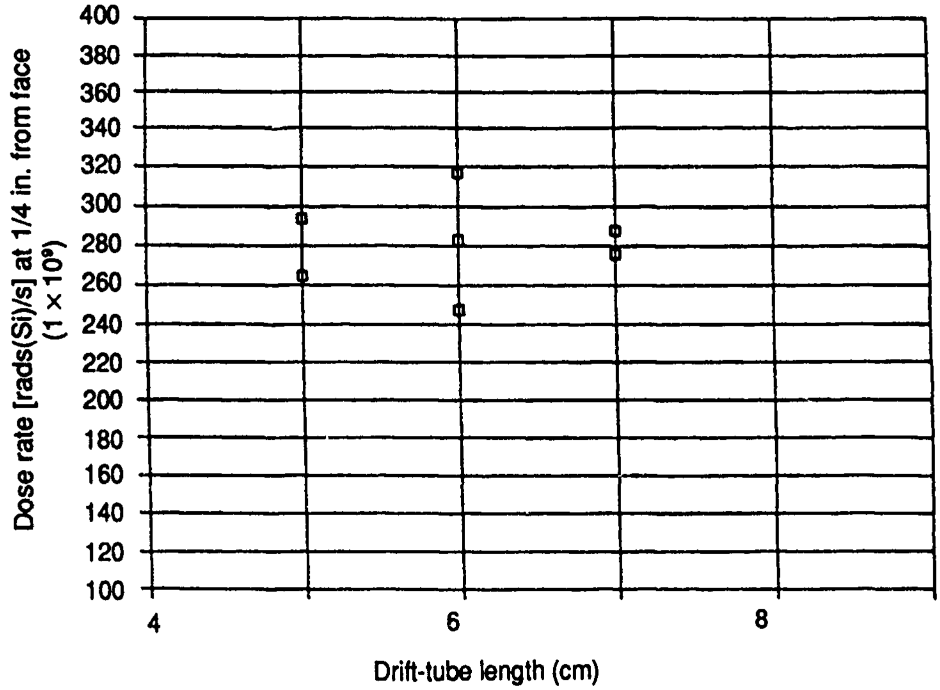
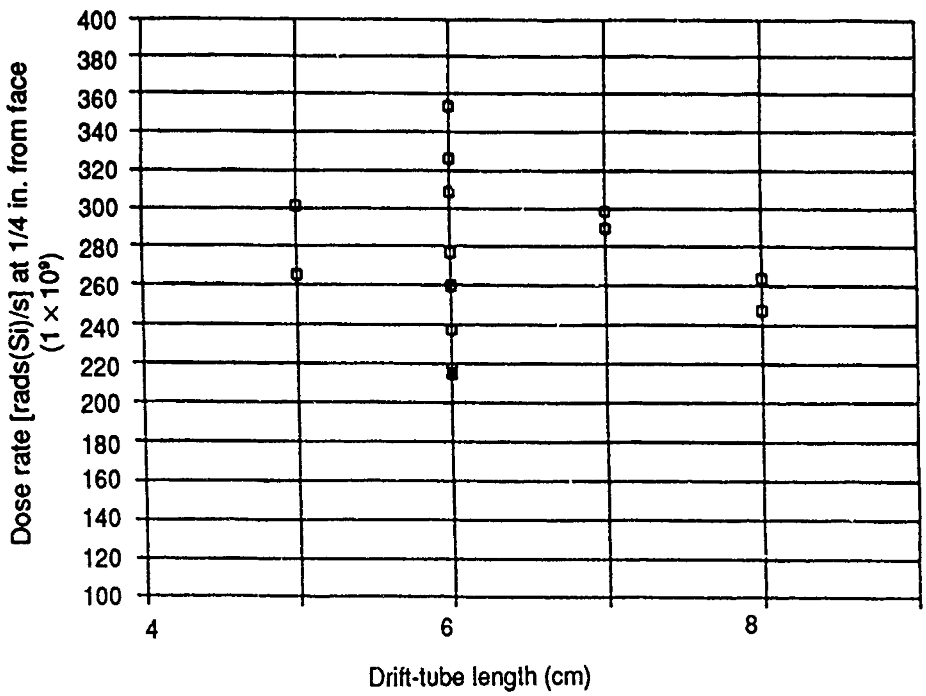


Figure 3. HIFX beam pinch at 0.1 Torr, ¼ in. from face.



pulse width narrowed from 25-ns FWHM to 18-ns FWHM with a risetime of about 8 ns (as measured by the CXRD). In figures 4 and 5 it is not possible to determine with confidence the tube length corresponding to peak dose rate, but it appears reasonable to assume by linear extrapolation that the peak dose rate will not be any larger than the peak value seen in figure 3, at 0.1 Torr. At this pressure (0.1 Torr),

Figure 4. HIFX beam pinch at 0.25 Torr, ¼ in. from face.

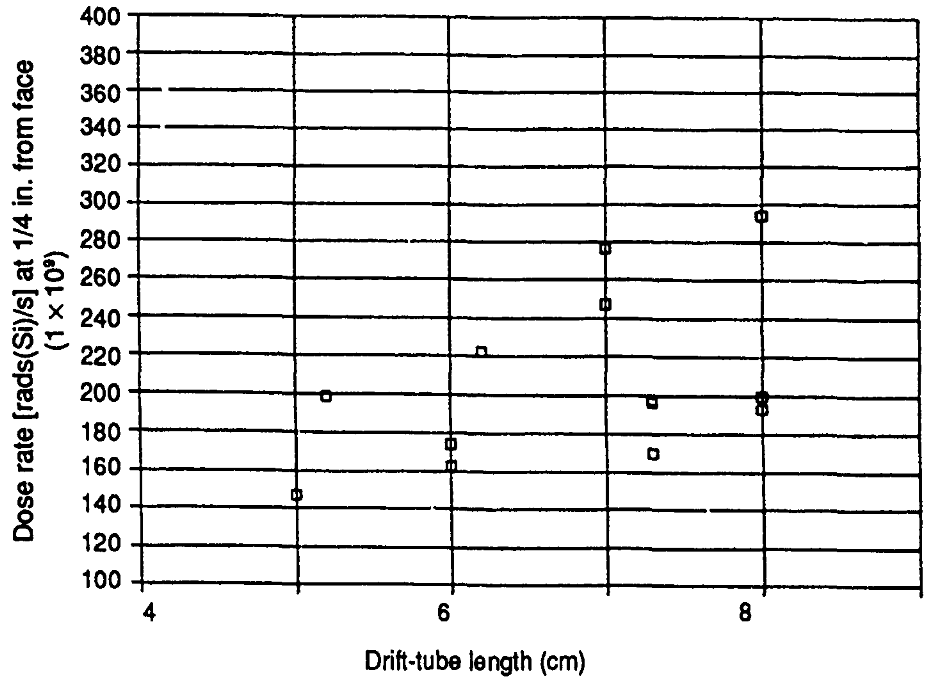
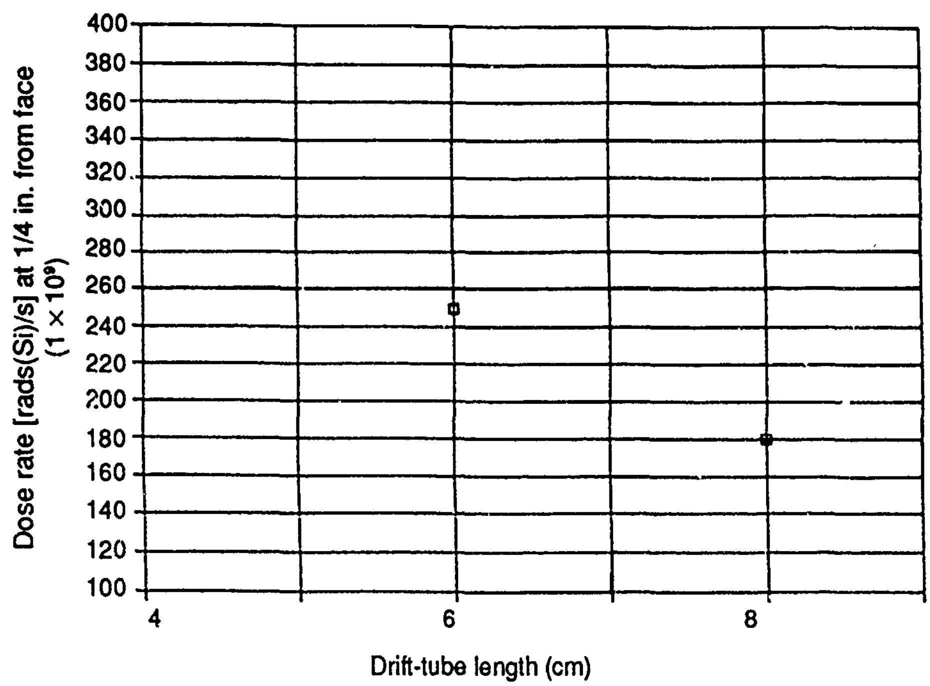


Figure 5. HIFX beam pinch at 0.5 Torr, ¼ in. from face.



maximum dose rate was achieved with a drift-tube length of 6 cm. In figure 3, we see that the eight shots ranged from 2.1×10^{11} to 3.5×10^{11}, with a mean and median of about 2.7×10^{11} rads(Si)/s. HIFX in the normal photon mode averages about 5×10^{10} rads(Si)/s. Thus, it appears that even this simple beam-pinch system increases the dose rate roughly by a factor of 5 and provides a faster risetime—8 ns.

Figures 6 and 7 show results at the second TLD location (¾ in. from Al plate). Figure 6 combines all pressures used with drift-tube length as the independent variable, and figure 7 combines all lengths with pressure as the independent variable. These data indicate that a 6-cm-long tube at a pressure of 0.1 Torr is optimum. When evaluating the readings of these second TLDs, one needs to consider the shadowing effects of the first TLD pillbox on the second TLD. Based on a simple calculation, we estimate that the reported values of the second TLDs should be increased by at least 10 percent.

In figure 8, the ratio of the first TLD reading to the second TLD reading is plotted versus the dose rate of the first TLD. High dose rates at the first TLD mean good beam pinches; i.e., the photons are concentrated at the location of the first TLD. It was anticipated that a good beam pinch would result in more beam divergence and consequently a more rapid drop-off in the z direction, resulting in a higher ratio of the first TLD reading to the second reading. Figure 8 confirms this conclusion.

After the first series of shots, a shot was taken with a 6-cm drift-tube length and 0.1-Torr pressure, using an array of TLDs five wide (r direction) and three deep (z direction).

Figure 9 shows the radial drop-off in dose rate for three distances from the movable plate: ¼, ¾, and 1¼ in. As the modest peak dose rate at ¼ in. (2.0×10^{11} rads(Si)/s) indicates, this shot was not one of the better pinches. Even so, the radial drop-off at z = ¼ in. is significant, with the

Figure 6. HIFX beam pinch at ¾ in. from face, showing drift-tube length.

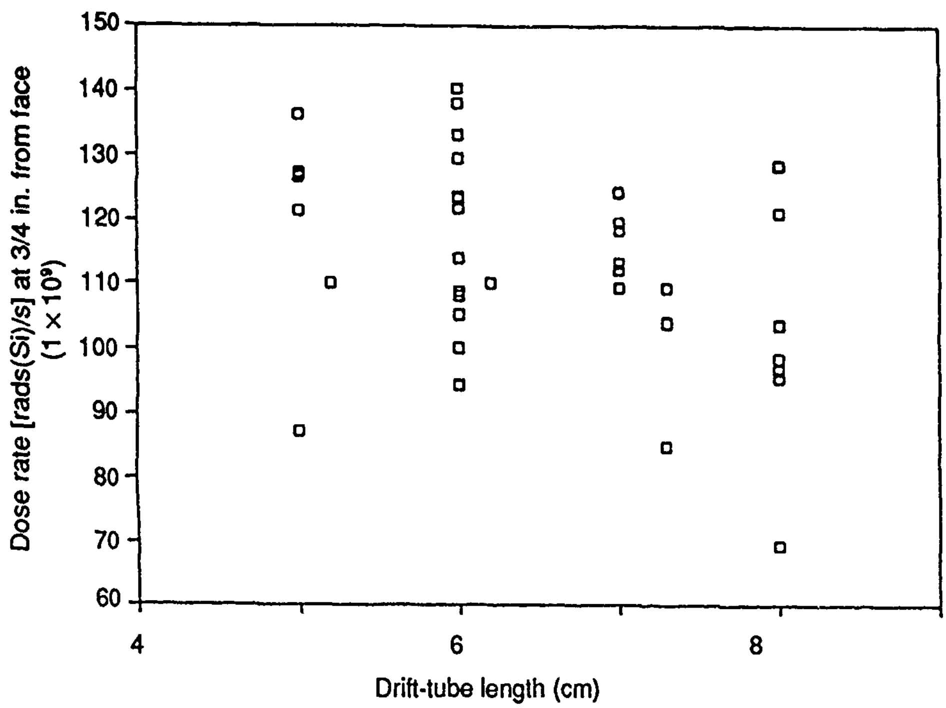


Figure 7. HIFX beam pinch at ¾ in. from face, showing pressure.

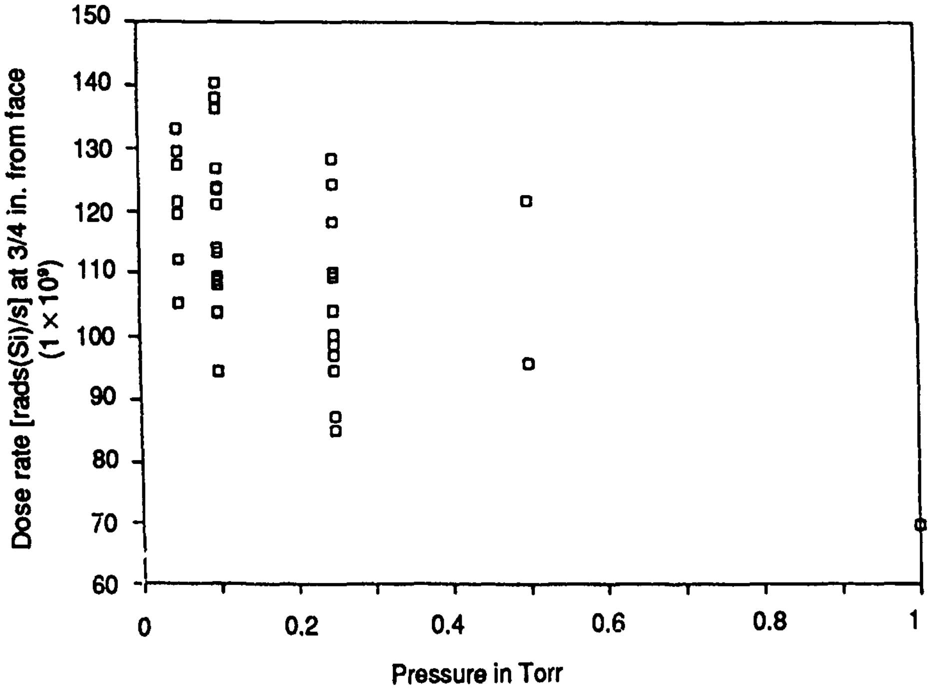
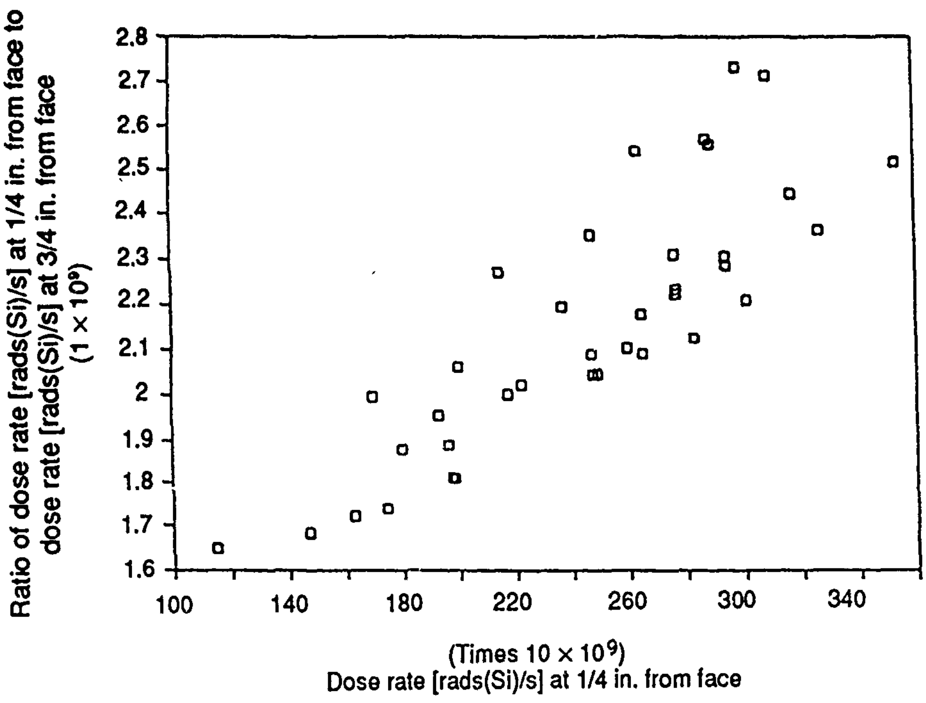
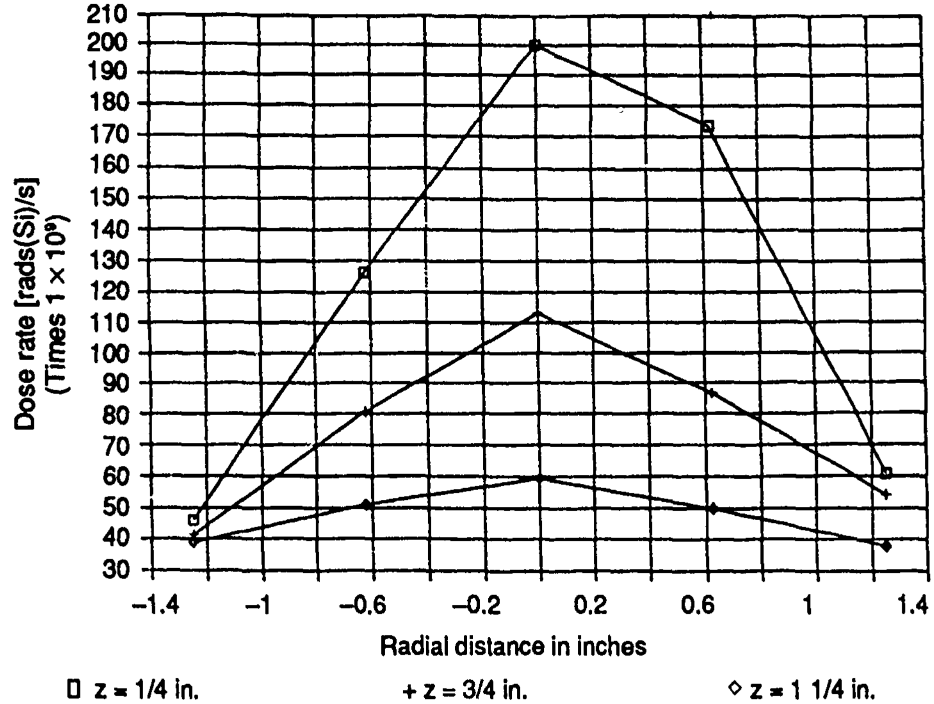


Figure 8. HIFX beam pinch. Ratio of dose rate at ¼ in. to dose rate at ¾ in.



radiation down by a factor of 2 to 2.5 at $r = 1$ in. and down by about a factor of 4 at $r = 1.25$ in. Even more rapid drop-off would be expected with better pinches which more closely approximate a point source.

Figure 9. HIFX beam pinch (tube length, 6 cm; pressure, 0.1 Torr).



7. Conclusions

The peak photon-radiation dose rate of the HDL HIFX facility has been increased by at least a factor of 5 through the use of custom, beam-pinching hardware. With this hardware, the facility can now routinely provide a dose rate of 2.7×10^{11} rads(Si)/s, at a distance of ¼ in. from the drift-tube face, while providing excellent radial drop-off to minimize irradiation of items surrounding the device under test. Even at a distance of ¾ in. from the face, the facility can now routinely provide a dose rate $>1 \times 10^{11}$ rads(Si)/s. The experimental results show the optimum operating parameters of the beam-pinching hardware to be a drift-tube length equal to 6 cm with an internal N gas pressure of 0.1 Torr.

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